CARBON MONOXIDE IN THE PRODUCTS OF COMBUSTION FROM NATURAL GAS BURNERS

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ABSTRACT

Many natural-gas appliances are notoriously inefficient. Solid top stoves with low set burners and grid top stoves with low set burners consume two to eight times as much gas as stoves with raised burners and grid tops. On account of the liberation of carbon monoxide, a poisonous gas, with the products of combustion when the flame is improperly aerated it is not practical to place burners at the distance from utensils where the maximum efficiency is obtained. Burners of the "star" type should be placed about 1 inch, the "slot" burner about ¾ inch, and the "disc" type about 1¼ inches from utensil.

From the many tests for carbon monoxide made with five different burners and different types of flames at rates of consumption of 6.0 and 8.0 cubic feet per hour (6480 and 8640 Btu per hour), the maximum rate of liberation of carbon monoxide was found to be 0.25 cubic foot per hour and was obtained with a very soft flame and a close position of utensil which caused the flame to "float" and extend up the side of utensil. It is not a dangerous rate unless one works directly over the burner, or several burners are in use at the same time for several hours, or the room is unventilated.

No carbon monoxide was found where the blue inner cone of the flame was not allowed to touch the utensil. A yellow flame will produce carbon monoxide at a rate much greater than a blue flame when the utensil is so close to the burner as to cause a floating flame.

A natural gas flame was found to be smothered from deficiency of oxygen when the content of the atmosphere had been diminished to about 15.5 per cent. When one considers the natural ventilation which takes place through the windows and doors it would seem that the danger from carbon monoxide poisoning with natural gas top burners is quite remote.

CONTENTS

I. INTRODUCTION

Carbon monoxide, a very poisonous gas, is produced in combustion processes where there is a deficiency of oxygen for completely burning the carbon in the gas to carbon dioxide. A condition favorable for the production of carbon monoxide results with the usual type of gas burner when the flame is insufficiently aerated by placing the burner too close to the utensil.

The efficiency of natural gas burners is greatly increased by placing the burner close to the utensil. It is therefore very important to know how close the burner can be placed to the utensil without producing dangerous quantities of carbon monoxide. The air shutter adjustment of the burner which determines the characteristic of the flame has also much to do with securing good combustion.

We know of no tests that have been made of the amount of carbon monoxide that can be liberated from the different types of domestic burners when operated with different flame characteristics, different rates of consumption of natural gas, and different positions of burner from utensil. It was therefore considered of great importance to investigate this matter very thoroughly.

The tests reported in this paper were made in connection with the investigation conducted by the Bureau of Standards on the design and efficiency of natural gas burners. The tests were made in the Bureau of Mines gas laboratory in Pittsburgh. This laboratory was splendidly equipped to make the gas analyses, and it was agreed between the Bureau of Standards and the Bureau of Mines to investigate and report jointly this phase of the problem.

Three different types of domestic gas burners as commonly used were tested under a variety of conditions of operation, with especial reference to conditions where carbon monoxide would be most likely produced.

The products of combustion were analyzed for the amount of carbon monoxide, carbon dioxide, oxygen, and nitrogen. Under some conditions very small amounts of partly oxidized products, as aldehydes, were known to be present, but in proportions too small to be tested by the usual methods of analysis.

Special acknowledgment is made to W. L. Parker, assistant chemist, Bureau of Mines, for the painstaking manner in which he made the analyses of the products of combustion here reported. J. H. Eiseman and G. B. Shawn, laboratory assistants, Bureau of Standards, assisted in making the burner tests.

II. CARBON MONOXIDE

Carbon monoxide is a colorless and odorless gas slightly lighter than air, specific gravity 0.967 (air = 1.0), and burns with a pale blue flame. It is one of the combustible constituents of water gas, coal gas, and producer gas. The gas is very poisonous, and it is due to this that so many deaths are caused annually by the accidental or intentional inhaling of artificial gases.

Owing to the fact that carbon monoxide is colorless, odorless, tasteless, and not easily detected by the ordinary senses, it can be present in very dangerous proportions before being detected.

1. ACTION OF CARBON MONOXIDE

Carbon monoxide combines with the hemoglobin of the blood and temporarily destroys its function as an oxygen carrier. After continued exposure a large part of the hemoglobin becomes inactive, depending on the concentration of carbon monoxide present in the atmosphere. The affinity of carbon monoxide for hemoglobin is 250 to 300 times as great as oxygen, and it is easily seen why a small percentage of carbon monoxide soon becomes very dangerous to health when inhaled for some time.

Haldane[1] makes the following statement:

> The poisonous action of carbon monoxide is due to the fact that this gas combines with hemoglobin, the colored blood constituent which normally carries oxygen to the tissues. As the carbon monoxide takes the place of oxygen the blood is more or less prevented from carrying oxygen, and the animal dies, if the process has gone far enough, from want of oxygen. The extent to which the hemoglobin becomes saturated with carbon monoxide depends in the long run on the relative mass influences of the oxygen and carbon monoxide present in the blood as it leaves the lungs.

When the person is removed to an atmosphere free from carbon monoxide, the oxygen of the air displaces the carbon monoxide taken up by the blood. The action, however, is slow.

2. SYMPTOMS OF CARBON MONOXIDE POISONING

The symptoms of carbon monoxide poisoning are described by R. R. Sayers [2] and H. R. O'Brien,[3] who state that:[4]

> The victim of acute carbon monoxide poisoning usually experiences the following symptoms: A tight-stretched-skin feeling across the forehead; a frontal headache, dull and intermittent at first, later more severe and continuous; this headache is replaced or masked by a typical one at the base and back of the skull, which causes the sufferer to hold his head as far back as possible in an effort to obtain relief; dizzi-

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[1] Haldane, J. S., Methods of air analysis, p. 109; 1912.

[2] Chief surgeon, U. S. Bureau of Mines.

[3] Car surgeon, U. S. Bureau of Mines.

[4] Forthcoming technical paper on "The treatment of carbon monoxide poisoning."

ness, nausea (feeling of sickness), and lassitude also occur. The pulse is at first normal, but later becomes full and rapid, the skin is flushed, the respiration becomes more rapid with exposure to the gas and later irregular. If the exposure is sufficiently long or the concentration sufficiently great, confusion, convulsions, and unconsciousness develop. As the victim recovers, he remains weak for some time; this is especially true of the muscles of his legs. The headache persists and may be extremely severe. The nausea may be sufficient to produce vomiting. All the symptoms are accentuated by exercise. When a man is overcome by large concentrations the symptoms follow each other rapidly and he may quickly fall unconscious. The rate at which a man is overcome and the sequence in which the symptoms appear depend on several factors: The concentration of the gas, the extent to which he is exerting himself, the state of his health and individual predisposition, and the temperature, humidity, and air movement to which he is exposed. Exercise, high temperature, and great humidity, with no air movement, tend to increase respiration and heart rate, and consequently result in more rapid absorption of carbon monoxide.

As to the quantity of carbon monoxide which may be present before symptoms develop, Haldane [5] states that an addition of 0.05 per cent of carbon monoxide in pure air is just sufficient to produce in time slight symptoms in man. In another experiment Haldane breathed air containing 0.027 per cent of carbon monoxide for 3½ hours. No symptoms were apparent, except perhaps unusual shortness of breath and palpitation of the heart on running up stairs.

Of the more recent authorities on the effect of carbon monoxide on man, Henderson [6] and others found that 0.06 per cent of carbon monoxide in air frequently gave headaches and other symptoms when the subjects were at rest and exposed for one hour. Since carbon monoxide symptoms not only depend upon the concentration of the carbon monoxide present in the atmosphere but also upon the time of exposure, the rate of breathing, or, in other words, the amount of work or exercise being done, and the physical state of the subject, a definite stated concentration of carbon monoxide in air above which symptoms develop can not be given which will apply for all cases. Henderson [6] and others state:

> The whole matter may be even more simply summed up in a single expression involving the time measured in hours, the concentration of carbon monoxide in air in parts per ten thousand and a constant for each degree of physiological effect. The physiological effect of all concentration and times (within reasonable limits) may be defined as follows:
>
> (1) Time × concentration = 3, no perceptible effect.
> (2) Time × concentration = 6, a just perceptible effect.
> (3) Time × concentration = 9, headache and nausea.
> (4) Time × concentration = 15, dangerous.
>
> Physical exertion and increased breathing would reduce the constant in the first equation from three to two, one, or even less; and would affect the other equations correspondingly.

[5] Haldane, J. S., The action of carbon monoxide on man, J. Phys., 18, p. 430; 1895.

[6] Henderson, Yandell, Haggard, H. W., Teague, M. C., Pierce, A. Wunderlich, Report of tunnel gas investigation, problem No. 2. Forthcoming publication of the Bureau of Mines.

From the above, the maximum percentage of carbon monoxide allowable for continuous exposure from a hygienic standpoint should not be greater than 0.02 per cent, and for intermittent exposures of 1 hour not greater than 0.04 per cent.

III. EFFECTS OF CARBON DIOXIDE

As regards the amount of carbon dioxide present that may give rise to symptoms of poisoning, Haldane and Smith [7] found that these symptoms do not appear until 3 to 4 per cent of the gas is present, when the breathing becomes slightly affected. Working under these conditions men become quickly fatigued. The symptoms are more marked as the percentage of carbon dioxide is increased, until at 12 to 15 per cent the patient soon becomes unconscious.

More recent information on the action of carbon dioxide on men, experiments performed at the Bureau of Mines by Dr. R. R. Sayers,[8] is of interest. Quoting Dr. Sayers from his report:

> The effect of breathing 0.5 per cent of carbon dioxide in air, according to Hill, is a slight and unnoticeable increase in the ventilation [9] of the lungs and a little more carbon dioxide is produced in the muscles; 2 per cent increases the ventilation of the lungs about 50 per cent; 3 per cent, about 100 per cent; and 5 per cent, about 300 per cent; while 10 per cent can not be endured for more than a minute or so. The effects are headache, sweating, dimness of vision, and tremor. In some experiments carried out at the Bureau of Mines experiment station, Pittsburgh, Pa., it was found that about 2 per cent of carbon dioxide in oxygen produced a slight increase in lung ventilation, but no subjective symptoms; 5 per cent in oxygen caused an increase in lung ventilation of about 100 per cent, but no other signs or symptoms; 7.2 per cent produced 200 per cent increase in lung ventilation and moderate sweating, and a slight fullness in the head was experienced after breathing the mixture for 10 minutes; 9 to 10 per cent produced about 300 per cent increase in lung ventiliaton, and the subject complained of frontal headache and was dizzy and sweating at the end of 10 minutes. About 9 per cent of carbon dioxide in oxygen was breathed by some of the subjects for as long as 45 minutes, but the breathing was very laborious, and dizziness, headache, and sweating were marked. In view of this data, we can conclude that, while it is possible to breathe 9 or 10 per cent of carbon dioxide in oxygen, a percentage above 5 per cent will cause noticeable effects

The above experiments made by the Bureau of Mines were conducted with carbon dioxide and oxygen mixtures; for carbon dioxide and air mixtures the value should be as low or lower than those for carbon dioxide and oxygen mixtures. In other words, if 4 per cent is taken as the maximum amount of carbon dioxide that can be tolerated in air, carbon monoxide is at least one hundred times more dangerous than carbon dioxide.

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[7] Haldane, J. S., and Smith, Lorain, Physiological effects of air vitiated by respiration, J. Path. Bact. 1, p. 174; 1892.

[8] R. R. Sayers, Physiological effects due to the use of rescue apparatus, Coal Trade Bulletin, 45, p. 28, 1921.

[9] The amount of air flowing through the lungs in a given time.

IV. EFFECT OF DIMINISHED OXYGEN SUPPLY

Normal, pure, dry air, when analyzed by volume, consists of 20.93 per cent oxygen, 79.04 per cent nitrogen, and 0.03 per cent carbon dioxide. Included in the nitrogen content is about 1 per cent of the four inactive gases, argon, krypton, neon, and xenon, argon largely predominating. Every cubic foot of natural gas (assuming the gas to consist of 88.7 per cent methane and 10.7 per cent ethane as used in these tests) requires 2.15 $ft.^3$ of oxygen for complete combustion or 10.3 $ft.^3$ of air. An ordinary standard domestic natural-gas burner should consume gas at a rate not greater than about 8 $ft.^3$ per hour when at the proper distance from the utensil (1 in.). At a rate of 8 $ft.^3$ of gas per hour, 82.4 $ft.^3$ of air per hour will be required for complete combustion.

It is evident that in a closed room the oxygen percentage drops according to the rate of consumption of gas. In tests made with a burner consuming 8 $ft.^3$ of natural gas per hour in an air-tight room of approximately 1000 $ft.^3$ capacity it required 1.5 hours to reduce the oxygen content to 18 per cent. As a general average, the oxygen percentage probably never falls below 19 per cent. It is believed that ordinarily enough natural ventilation occurs to maintain an oxygen value of at least 19 per cent. Natural gas will not burn if the oxygen is reduced as low as 15.5 per cent. An individual when at rest, however, may tolerate oxygen percentages below 13 per cent without serious effects other than a sense of fatigue.

V. TESTS OF PRODUCTS OF COMBUSTION FOR CARBON MONOXIDE

It was shown in the efficiency tests of natural-gas burners of standard size that a consumption of 6 to 8 $ft.^3$ per hour contained the maximum quantity of heat units that a standard burner would require if the burner were about 1 in. from the utensil. (See Bureau of Standards paper "How natural-gas burners can be improved," by I. V. Brumbaugh and G. B. Shawn.) Tests for carbon monoxide were made at these rates of consumption and different positions of utensil from burner, since the question of the maximum efficiency that can be safely secured with the various burners depended on how close to the utensil the burner could be placed without producing carbon monoxide in poisonous quantities.

There are many designs of natural-gas burners placed at different distances from the utensil, and the flame characteristics

of each are generally quite different. Even if the different designs of burners were placed at the same distance from the utensil, owing to the various air-shutter adjustments there would be still no uniformity of flame characteristic for the same rate of consumption. It was essential, therefore, to operate burners with definite ratios of volume of primary air injected into the burner to volume of gas consumed and at different rates of consumption and at the different positions of burner from utensil, in order to secure comparative data by which to determine the proper distance.

The method of operation and a description of the apparatus which was used to produce the different ratios of air to gas is described in Bureau of Standards Technologic Papers, No. 193, Design of atmospheric gas burners, by Walter M. Berry, I. V. Brumbaugh, G. F. Moulton, and G. B. Shawn; also in How natural-gas burners can be improved, by I. V. Brumbaugh and G. B. Shawn.

1. SAMPLING APPARATUS, METHOD OF SAMPLING, AND METHOD OF ANALYSIS

The apparatus for sampling the products of combustion was essentially as shown in Fig. 1. First, a definite number of cubic feet of gas per hour was supplied to the burner, and a definite number of cubic feet of primary air per hour was introduced into the burner through the air-shutter opening. Then an aluminum utensil *g* filled with 5 pounds of tap water was adjusted at a definite height over the burner. The hood *f* was then placed over the utensil and burner, and the products of combustion and the excess air were thus passed through the top of *f*. It was soon observed that the natural draft mixed too much excess air with the products of combustion. By closing a large portion of the opening at the top of the hood the excess air was decreased without interfering with the natural operation of the burner. About 2 minutes after the utensil was placed over the burner a sample of the products of combustion was taken, as follows: A gas sample tube *b* previously filled with water that was saturated with combustion product gases from the burners was connected to tube *d*. The tube *e* and connections were then cleared of dead gas by opening clamp *j* and working the bulb aspirator *a*. The water in sample tube *b* when pinch clamps *c* and *i* were opened was allowed to flow out, drawing in a sample of the products of combustion from the burner. When all but a few drops of water had left the

tube, the pinch clamps were closed and the sample was removed for analysis. At the beginning of the work repeat samples were taken 4 minutes after the utensil was placed above the burner. These samples in each case checked the 2-minute samples, and thereafter only one sample of gas was taken for each burner adjustment. The temperature of the water in the utensil was approximately 100° F (37.8° C) at the time of sampling.

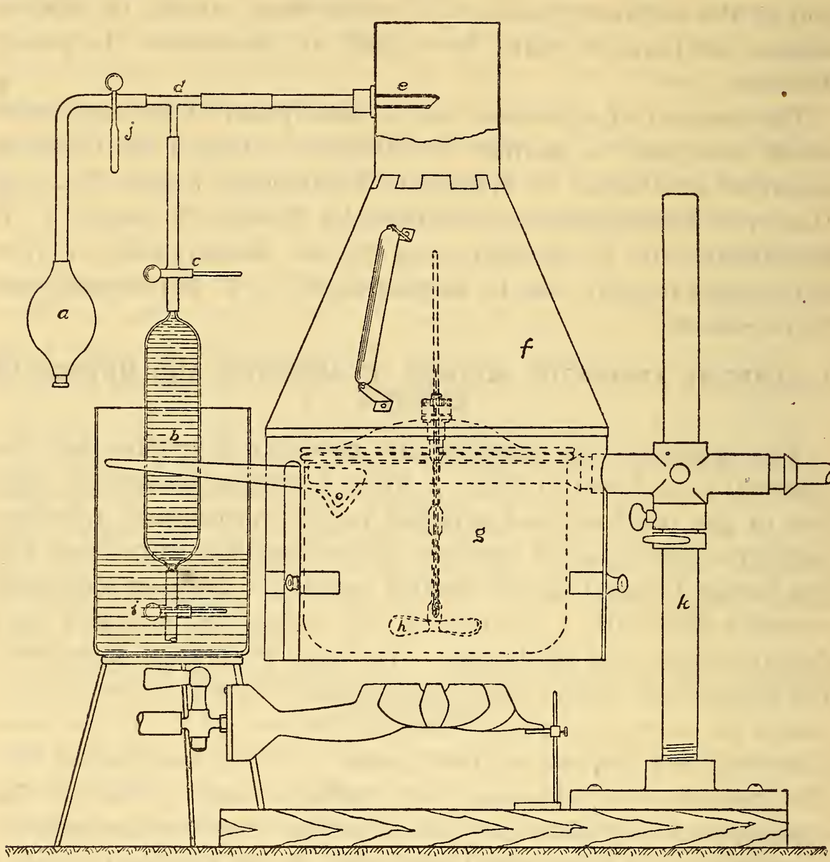

FIG. 1.—*Apparatus used for obtaining sample of products of combustion from burners.*

The samples were analyzed on the Haldane gas analysis apparatus of the usual type used by the U. S. Bureau of Mines for analyses of mine air samples. This apparatus has a limit of accuracy for carbon dioxide, oxygen, carbon monoxide, hydrogen, and methane of 0.02 per cent. For method of use and other details see U. S. Bureau of Mines Bulletin 42, The sampling and examination of mine gases and natural gas, by G. A. Burrell and F. M. Seibert.

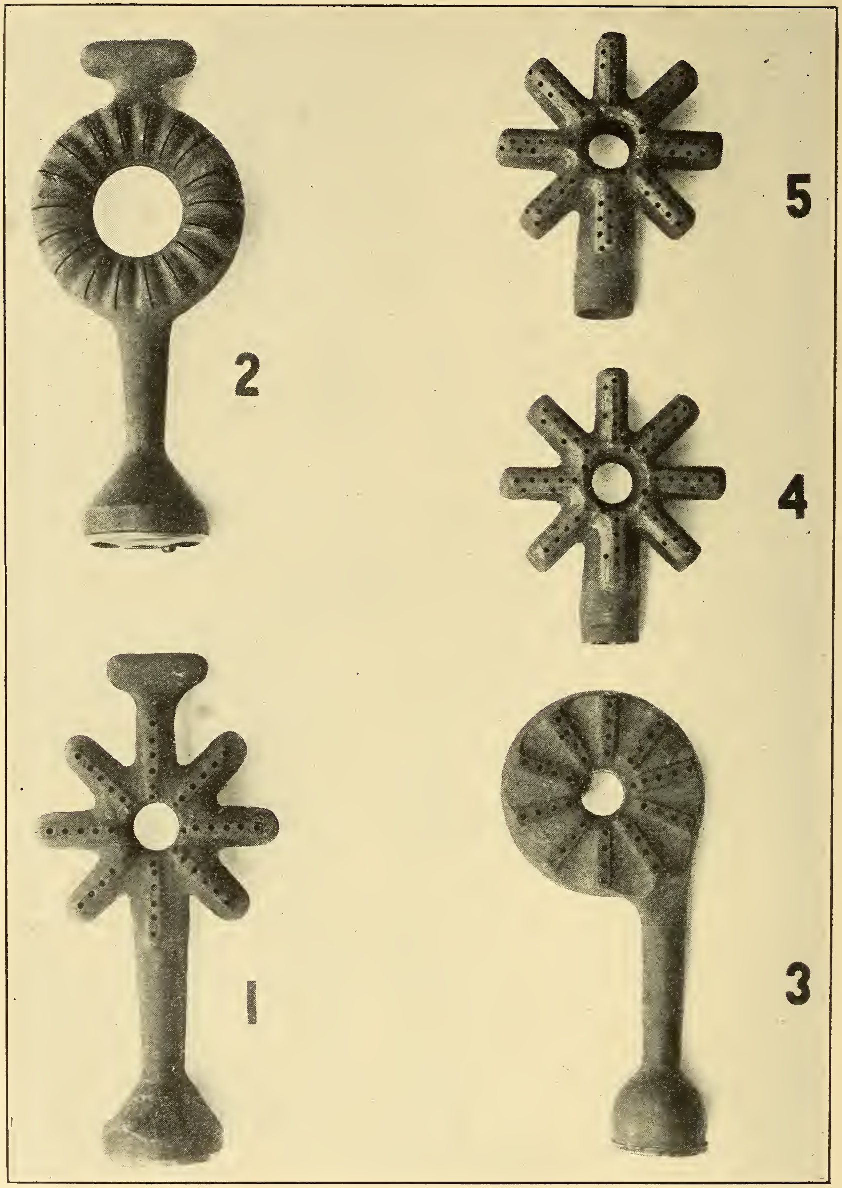

FIG. 2.—*Burners used in testing products of combustion for carbon monoxide*

2. BURNERS TESTED

The five different burners which were used to make the tests herein reported are shown in Fig. 2. Of the present domestic burners in operation with natural gas the type shown by No. 1, and known as the "star" burner, is most commonly used. No. 2 is called the "slot" or "sawed" burner, and No. 3 is of the "disc" type. Burners Nos. 4 and 5 are star burners with specially spaced ports. These two burners were fitted to improved injecting tubes when tested. The photograph shows them without the injecting tubes. Burners Nos. 1 and 3 were tested when the ports were of No. 40 drill size and also when of No. 30 drill size.

3. TABULATION OF RESULTS

The results of the tests of the products of combustion are tabulated in Table 1. The data are arranged to show separately the tests of each burner, because different types and different designs of any one type are rarely found in the same installation. The tests of the different positions of utensil from burner are grouped according to constant rates of consumption. The different rates of consumption are further grouped according to the ratio of volume of air injected into the burner to the volume of gas consumed.

TABLE 1.—Results and Conditions of Carbon Monoxide Tests

Type of burner	Gas rate	Air-gas ratio	Distance of utensil from burner	Cone height	Products of combustion air-free basis (per cent)				Formation of CO
					CO	CO_2	CH_4	N_2	
	Cu. ft.		In.	In.					Ft.³/hr.
Star burner (No. 1), 48 ports; No. 40 drill; port area, 0.36 sq. in.	6	1½:1	½	....	0.35	11.53	0.09	88.03	[a]0.19
	6	1½:1	¾	....	.35	11.48	.09	88.08	[a] .19
	6	1½:1	1	....	.24	11.45	.02	88.29	.14
	6	3:1	½	0.48	.20	11.80	.10	87.90	[a] .11
	6	3:1	¾	.48	.34	11.95	.08	87.63	[a] .18
	6	3:1	1	.48	.11	12.02	.03	87.84	.06
	6	5:1	½	.40	.20	11.96	.05	87.79	[a] .11
	6	5:1	¾	.40	.08	12.01	.00	87.91	.04
	6	5:1	1	.40	.00	12.14	.00	87.86	.00
	8	1½:1	¾	....	.29	11.48	.16	88.07	[a] .21
	8	1½:1	1	....	.24	11.83	.09	87.84	[a] .18
	8	1½:1	1¼	....	.32	11.88	.00	87.80	[a] .23
	8	3:1	½	.62	.23	11.48	.08	88.21	[a] .17
	8	3:1	¾	.62	.26	11.75	.06	87.73	[a] .19
	8	3:1	1	.62	.07	11.79	.04	88.10	.05
	8	5:1	½	.50	.10	11.46	.02	88.42	[a] .07
	8	5:1	¾	.50	.14	12.37	.00	87.39	[a] .10
	8	5:1	1	.50	.00	11.43	.00	88.57	.00
Star burner (No. 1); 48 ports; No. 30 drill; port area, 0.62 sq. in.	6	5:1	½	.37	.20	11.94	.03	87.83	[a] .11
	6	5:1	¾	.37	.36	11.78	.00	87.86	[a] .19
	6	5:1	1	.37	.14	11.92	.00	87.94	.08
	6	7:1	½	.27	.11	11.93	.00	87.96	[a] .06
	6	7:1	¾	.27	.06	12.44	.03	87.47	.03
	6	7:1	1	.27	.00	12.22	.00	87.78	.00
	8	5:1	½	.48	.16	11.77	.04	88.03	[a] .12
	8	5:1	¾	.48	.25	11.73	.04	87.98	[a] .18
	8	5:1	1	.48	.09	11.87	.02	88.02	.07
	8	7:1	½	.35	.27	11.82	.13	87.78	[a] .19
	8	7:1	¾	.35	.07	11.95	.05	87.93	[a] .05
	8	7:1	1	.35	.00	11.93	.00	88.07	.00

[a] Values which are averaged in Table 2.

TABLE 1.—Results and Conditions of Carbon Monoxide Tests—Continued.

Type of burner	Gas rate	Air-gas ratio	Distance of utensil from burner	Cone height	Products of combustion air-free basis (per cent)				Formation of CO
					CO	CO_2	CH_4	N_2	
	Cu. ft.		In.	In.					Ft.³/hr.
Disc burner (No. 3); 44 ports; No. 39 drill; port area, 0.34 sq. in.	6	3:1	¾	0.50	0.45	11.46	0.11	87.98	a0.25
	6	3:1	1	.50	.33	11.67	.00	88.00	a.18
	6	3:1	1¼	.50	.05	11.81	.00	88.14	.03
	6	5:1	½	.38	.20	11.65	.00	88.15	a.11
	6	5:1	¾	.38	.35	11.65	.11	87.89	a.19
	6	5:1	1	.38	.06	11.92	.00	88.02	.03
	8	3:1	¾	.69	.28	11.84	.04	87.88	a.20
	8	3:1	1	.69	.27	11.70	.04	88.03	a.20
	8	3:1	1¼	.69	.15	11.87	.00	87.98	.11
	8	5:1	½	.50	.10	11.97	.04	87.92	a.07
	8	5:1	¾	.50	.17	11.84	.06	87.99	a.12
	8	5:1	1	.50	.10	11.95	.02	87.95	.07
Disc burner (No. 3); 44 ports; No. 30 drill; port area, 0.57 sq. in.	6	5:1	¾	.41	.32	11.97	.11	87.60	a.17
	6	5:1	1	.41	.27	11.70	.00	88.03	a.15
	6	5:1	1¼	.41	.03	11.63	.00	88.34	.02
	6	7:1	½	.34	.11	11.76	.05	88.08	a.06
	6	7:1	¾	.34	.17	11.98	.03	87.82	a.09
	6	7:1	1	.34	.00	12.39	.00	87.61	.00
	8	5:1	¾	.50	.21	12.08	.00	87.71	a.15
	8	5:1	1	.50	.20	11.73	.07	88.00	a.15
	8	5:1	1¼	.50	.10	11.82	.00	88.08	.07
	8	7:1	¾	.40	.18	11.99	.09	87.74	a.13
	8	7:1	1	.40	.05	12.10	.00	87.85	a.04
	8	7:1	1¼	.40	.00	12.10	.00	87.90	.00
Slot burner (No. 2); 18 slots; width 0.39 in.; port area, 0.64 sq. in.	6	5:1	½	.25	.32	12.12	.06	87.50	a.17
	6	5:1	¾	.25	.09	11.96	.00	87.95	.05
	6	5:1	1	.25	.00	12.14	.00	87.86	.00
	6	7:1	½	.16	.06	11.97	.00	87.92	a.03
	6	7:1	¾	.16	.00	12.00	.00	88.00	.00
	6	7:1	1	.16	.00	11.45	.00	88.55	.00
	8	5:1	½	.28	.16	11.82	.05	87.97	a.12
	8	5:1	¾	.28	.08	11.87	.05	88.00	.06
	8	5:1	1	.28	.00	12.10	.00	87.90	.00
	8	7:1	½	.20	.16	12.00	.00	87.84	a.12
	8	7:1	¾	.20	.00	12.09	.00	87.91	.00
	8	7:1	1	.20	.00	12.15	.00	87.85	.00
Star burner (No. 5); 67 ports; No. 36 drill; port area, 0.60 sq. in.	6	3:1	½	.40	.36	11.67	.05	87.92	.20
	6	3:1	¾	.40	.28	11.80	.00	87.92	.15
	6	3:1	1	.40	.00	11.90	.00	88.10	.00
	6	5:1	½	.31	.32	11.77	.08	87.83	.18
	6	5:1	¾	.31	.00	11.46	.00	88.54	.00
	6	5:1	1	.31	.00	11.97	.00	88.03	.00
	6	7:1	½	.25	.16	11.51	.10	88.23	.09
	6	7:1	¾	.25	.00	11.97	.06	87.97	.00
	6	7:1	1	.25	.00	11.84	.00	88.16	.00
	8	5:1	½	.37	.22	11.77	.02	87.99	.16
	8	5:1	¾	.37	.25	11.68	.00	88.07	.18
	8	5:1	1	.37	.07	11.90	.05	87.98	.05
Star burner (No. 6); 100 ports, No. 36 drill; port area, 0.90 sq. in.	8	3:1	½	.41	.17	11.57	.00	88.26	.13
	8	3:1	¾	.41	.08	11.53	.00	88.39	.06
	8	3:1	1	.41	.00	11.69	.00	88.31	.00
	8	5:1	½	.30	.13	11.70	.05	88.12	.10
	8	5:1	¾	.30	.15	11.70	.02	88.13	.11
	8	5:1	1	.30	.00	11.90	.00	88.10	.00
	8	7:1	½	.22	.12	11.57	.02	88.29	.09

a Values which are averaged in Table 2.

The values of the products of combustion on an air-free basis were computed as follows: Since normal air contains 20.93 per cent oxygen, if the oxygen percentage found in the sample of the

products of combustion is divided by 20.93, the resulting value gives the proportion of air present. This factor subtracted from 1.0 and divided into the different percentages of the analysis of the sample gives the air-free percentages shown in the table. For example, take the first analysis given in Table 1. The products of combustion, as sampled, contained:

	Per cent
CO =	0.16
CO_2 =	5.20
O_2 =	11.48
CH_4 =	.04
N_2 =	83.12
Total......	100.00

Then, since the sample contained 11.48 per cent oxygen, $\frac{11.48}{20.93}=0.549$, proportion of air in sample; and $1.0-0.549=0.451$, proportion of products of combustion in sample. Therefore, on the air-free basis,

$$CO = \frac{0.16}{0.451} = 0.35 \text{ Per cent}$$

$$CO_2 = \frac{5.20}{0.451} = 11.53$$

$$CH_4 = \frac{0.04}{0.451} = 0.09$$

$$N_2 = 88.03 \text{ by difference}$$

Total.... 100.00

The values of the rate of production of carbon monoxide in terms of cubic feet per hour shown in Table 1 were computed as follows: The average composition of the natural gas used in the tests contained:

	Per cent
Methane (CH_4) =	88.7
Ethane (C_2H_6) =	10.7
Nitrogen (N_2) =	.6
Total........	100.0

The above values for methane and ethane were determined by calculation of the contraction and carbon dioxide produced when a given quantity of natural gas was burned by the slow combustion method. The method gives the percentage of the two predominating hydrocarbons present. In reality the natural gas used contained a small amount of propane and traces of butane. The only available method for obtaining more than two saturated paraffin hydrocarbons in a natural gas is by fractionation analysis at low temperatures and pressures, using liquid air in oxygen.

Since the above method of reporting as to the two predominating hydrocarbons is correct with regard to the carbon content in a cubic foot of gas, the more tedious and expensive method of analysis using liquid air was not used.

One cubic foot of methane when completely burned produces 1 ft.^{3} of carbon dioxide, as the following equation indicates:

$$CH_4 + 2O_2 = CO_2 + 2H_2O.$$

Also when partially oxidized to carbon monoxide, 1 ft.^{3} of carbon monoxide is produced per cubic foot of methane, thus

$$CH_4 + O_2 = CO + H_2O.$$

Therefore, whether methane is completely oxidized to carbon dioxide or partially oxidized to carbon monoxide, or remains as unconsumed methane, the total quantity of these gases from 1 ft.^{3} of methane will always equal 1 ft.^{3}

When ethane is completely burned to carbon dioxide and water vapor, 1 ft.^{3} will produce 2 ft.^{3} of carbon dioxide according to the following equation:

$$C_2H_6 + 3\tfrac{1}{2}O_2 = 2CO_2 + 3H_2O.$$

Also, when partially oxidized to carbon monoxide each cubic foot of ethane produces 2 ft.^{3} of carbon monoxide; thus—

$$C_2H_6 + 2\tfrac{1}{2}O_2 = 2CO + 3H_2O.$$

Therefore, 1 ft.^{3} of ethane produces a total of 2 ft.^{3} of carbon dioxide and carbon monoxide irrespective of the relative percentages of each.

Going back to natural gas consisting of 88.7 per cent methane and 10.7 per cent ethane, in order to determine the total amount by volume of carbon monoxide produced per cubic foot of gas burned,

Multiply 0.887 by 1.0 = 0.887, and
Multiply 0.107 by 2.0 = 0.214,

which gives a total of 1.101 ft.^{3} of carbon monoxide and carbon dioxide per cubic foot of gas consumed.

Then let a = per cent of CO (air free basis)
b = per cent of CO_2 (air free basis)
c = per cent of CH_4 (air free basis)

and $\frac{a}{a+b+c} \times 1.101 \times$ gas rate per hour = the cubic feet of carbon monoxide produced per hour. This is the important column of the table with respect to health and ventilation.

4. POSSIBLE ERRORS IN ANALYSIS

From the manner of making analyses the following errors for the test for carbon monoxide could occur: (1) Incomplete absorption of the CO_2 in the sample before the test for combustion of CO is made; (2) incomplete absorption of CO_2 after combustion; (3) incomplete combustion of CO in the sample, assuming the CO_2 absorptions to be complete. It is possible, therefore, that there could be a greater error than 0.02 per cent in some analyses if any one of the above enumerations occurred. It is assumed that the possible error of 0.02 per cent referred to results from inability to compensate the volume and read the burette more accurately on account of the tedious method of manipulation of a Haldane gas analysis apparatus. If it is assumed that there can be a possible error of at least ± 0.02 per cent in the analysis of any constituent, then in the case where calculations are made on the air-free basis, if the sample contained 50 per cent air the air-free calculations can be in error by at least ± 0.04 per cent.

5. SIGNIFICANCE OF RESULTS

Observations made during the progress of the tests showed that at the close positions (generally ½ to ¾ in.) depending on design of burner, rate of consumption, and flame characteristic, the baffling of the flame hindered the supply of secondary air, forced the blue inner cone of the flame to spread, and, to use a familiar expression, caused a "floating flame" which extended up the side of the utensil. Under the "floating flame" condition rate of formation of carbon monoxide was a maximum for any given ratio of air to gas. The data show that there are no appreciable differences in the rates of formation of carbon monoxide for rates of consumption of 6 and 8 ft.^{3} per hour when the "floating flame" condition is produced.

In order to form some opinion as to the effect of design of burners and their operation, the amounts of carbon monoxide produced at the "floating flame" positions of burners Nos. 1, 2, and 3 are averaged in Table 2. The importance of operating natural gas burners with the air shutter adjusted for the higher ratio of air to gas is clearly shown by this table.

STAR BURNER NO. 1.—The average of 0.20 ft.^{3} of carbon monoxide per hour with star burner No. 1 was obtained when the ports were of No. 40 drill size, and the air-gas ratio was 1½ to 1. At such a ratio a yellow flame is produced that deposits carbon on

the utensil. By increasing the air-gas ratio to 5 to 1 a good blue flame was produced and the carbon monoxide was reduced to 0.09 ft.^{3} per hour. The burner could not be operated at a higher ratio because the velocity of the air-gas mixture issuing from the burner ports exceeded the velocity of combustion. The size of the ports of burner No. 1 was increased to No. 30 drill in order to operate it at a higher ratio, and Table No. 2 shows that the carbon monoxide average increased from 0.09 to 0.15 ft.^{3} per hour for an air-gas ratio of 5 to 1. At 7 to 1 ratio the carbon monoxide averaged 0.10 ft.^{3} per hour. Increasing the size of the ports increased the width of the flame of each port, thus bringing the flames closer together and causing poor aeration of the total flame.

TABLE 2.—Average from Carbon Monoxide Tests (from Table 1)

[Rate of consumption 6.0 and 8.0 ft.^{3} per hour; floating flame condition]

Air-gas ratio	Carbon monoxide produced with—							
	Star burner (No. 1)			Disc burner (No. 3)			Slot burner (No. 2)	
	Positions	48 ports		Positions	44 ports		Positions	
		No. 40 drill	No. 30 drill		No. 39 drill	No. 30 drill		
	In.	cu. ft.	cu. ft.		cu. ft.	cu. ft.		cu. ft.
1½:1	½, ¾, 1, and 1¼	0.20						
3:1	½ and ¾	.16		¾ and 1	0.21			
5:1	½ and ¾	.09	0.15	½, ¾ and 1	.12	0.16	½	0.14
7:1	½ and ¾	(a)	.10	½, ¾, and 1	(a)	.09	½	.07

[a] Could not be tested on account of limit of operation (flames blow from ports).

DISC BURNER NO. 3.—Very similar results to those of the star burner were obtained with the disc burner, except that at respective ratios of air to gas a more appreciable amount of carbon monoxide was produced when the ports were of No. 39 drill size as compared with the star burner when the ports were of No. 40 drill size. This comparison is made not so much as to the size of ports but more especially for the total port area. The total port areas, as well as the size of ports, are approximately the same. There is no question but that the disk burner obstructs the flow of the supply of secondary air to the flame, which accounts for the higher amounts of carbon monoxide. The data show that the disc burner will produce slightly more carbon monoxide and at positions farther from the utensil than the star burner.

SLOT BURNER NO. 2.—The utensil must be ½ inch or closer to the slot burner to cause a floating flame with air-gas ratios of

5 to 1 and 7 to 1 at rates of 6 and 8 ft.^{3} per hour. This can be attributed to the short cone heights which are caused by the narrow slots. Since in general the closer a burner can be safely placed to the utensil, the higher the efficiency, the slot burner from this point of view should show better practical results than the star or disc type.

From the many tests, shown in Table 1, made under a variety of conditions, the maximum quantity of carbon monoxide was found to be 0.25 ft.^{3} per hour. Taking for comparison a room of 1000 ft.^{3} capacity, which can be considered as representative of the size of the average kitchen, and taking 0.04 per cent for the maximum limit of carbon monoxide permissible for healthful conditions for one hour's exposure, it would take over 1½ hours before the concentration reached 0.04 per cent if only one burner was operated and the room was unventilated. If as many as four burners were used under the same condition at one time, the carbon monoxide would have increased to 0.04 per cent in less than half an hour.

When one considers the natural ventilation which takes place through the windows and doors, it would seem that the danger from carbon monoxide poisoning from natural gas burners is quite remote. There may arise conditions where the housewife is working directly over a burner and may breathe the products of combustion containing dangerous percentages of carbon monoxide. These conditions would occur only at short intervals. The danger would be due not only to carbon monoxide, but to a slight extent to carbon dioxide and the deficiency of oxygen as well. Cases of this kind are probably very rare but possible. Owing to air currents set up in the room by the hot gases the carbon monoxide will always tend to be evenly diffused through the atmosphere.

6. EFFECT OF TEMPERATURE OF WATER IN UTENSIL ON CARBON MONOXIDE IN PRODUCTS OF COMBUSTION

In all the tests reported in Table 1 the water in the utensil was approximately 100° F (37.8° C) at time of sampling. Samples that were taken when the water was approximately 125° F (51.7° C) checked the 100° F samples. There was some question whether the rate of formation of carbon monoxide was as much when the water in the utensil was at boiling temperature. To compare the effect of temperature, the results of a few tests are given in Table 3. It is not clear why at the respective positions

more carbon monoxide was found with the star burner when the temperature of the water was 212° F as compared with 100° F, while the disk burner showed less carbon monoxide at 212° F as compared with 100° F. The data, therefore, are not definite and do not warrant a conclusion as to whether there is a difference in the rate of formation of carbon monoxide under the above conditions.

TABLE 3.—Effect of Temperature of Water on Carbon Monoxide in Products of Combustion (Air-free Basis)

[Star burner (No. 1), 8 prongs, 48 ports, No. 40 drill, 0.36 square inch port area]

Air-gas ratio	Position	Rate—6 ft.³ per hour, with—		Rate—8 ft.³ per hour, with—	
		Water approximately 100° F	Water boiling 212° F	Water approximately 100° F	Water boiling 212° F
	In.	Per cent	Per cent	Per cent	Per cent
3:1	½	0.20	0.28	0.23	0.29
	¾	.34	.40	.26	.33
5:1	½	.20	.39	.10	.13
	¾	.08	.10	.14	.23

[Disc burner (No. 3), 10 rows of ports—44 ports, No. 30 drill, 0.57 square inch port area]

Air-gas ratio	Rate—8 ft.³ per hour with—		
	Position	Water approximately 100° F	Water boiling 212° F
	In.	Per cent	Per cent
5:1	¾	0.21	0.16
	1	.20	.14
7:1	¾	.18	.11
	1	.05	.05

VI. IMPORTANCE OF PROPER VENTILATION

It is well known that for healthful purposes it is especially important to have ample ventilation where the products of combustion from burners of natural-gas appliances are liberated into the atmosphere of a room. Therefore it is of unusual interest to know to what extent the oxygen supply to a flame could be diminished before the deficiency of oxygen resulting from combustion would cause the flame to be completely smothered. It is perhaps of greater importance to know how much of the highly poisonous carbon monoxide can be produced under the above condition which would correspond to poor ventilation. To obtain such data a test was made when a burner was operated in a specially constructed air-tight room with no ventilation.

A standard star burner containing 48 ports of No. 40 drill size was used for the test. The burner was adjusted so as to burn with a yellow flame, which is characteristic of many of the worst installations of natural-gas burners. Approximately one and one-half volumes of air to one of gas were injected into the burner with the gas. The gas rate was regulated so that the burner consumed about 8 ft.³ of natural gas per hour. After these preliminary regulations had been made an aluminum utensil was filled with water and placed 1 inch above the burner. The outlets of the room were then closed and the time recorded. A sample of the atmosphere in the room was taken each half hour until the flame went out. Just before taking each sample, the fan in the room was run for about 3 minutes to thoroughly mix the products of combustion with the atmosphere inside the room.

Table 4 shows the results of the test from the time when the burner was lighted until the flame went out. The curves of Fig. 3 show graphically the increase of carbon dioxide and decrease of oxygen, the increase of nitrogen, the increase of methane and increase of carbon monoxide. The test shows very clearly the necessity of having good ventilation in rooms where burners are used for long periods of time. The room had a capacity of approximately 1000 ft.³, which is believed to be near the capacity of the average kitchen. The burner using about 8 ft.³ of gas per hour at the end of 1.5 hours reduced the oxygen percentage from 20.9 to about 18 per cent and the carbon dioxide percentage rose to over 1.5 per cent. At the time the flame went out the oxygen content in the room had been reduced to less than 15.5 per cent and the carbon dioxide content was 3 per cent. The atmosphere also contained 0.16 per cent of carbon monoxide, which was an extremely poisonous concentration.

TABLE 4.—Analysis of Atmosphere in Unventilated Room of 1000 Cubic Feet Capacity

Test	Hours after beginning test	Gas consumed (cu. ft.)	Temperature of room [a]	Percentage composition of air in room					Remarks
				CO_2	O_2	CO	CH_4	N_2	
			°F						
1	0.0	0.0	78.5	0.03	20.93	0.00	0.00	79.04	Start of test
2	.5	....	89.5	.58	19.92	.02	.02	79.46	
3	1.0	....	93.0	1.07	19.02	.04	.02	79.85	
4	1.5	....	96.0	1.60	18.05	.05	.05	80.25	
5	2.0	....	97.0	2.08	17.24	.05	.05	80.58	
6	2.5	....	97.0	2.51	16.38	.08	.07	80.96	
7	3.0	....	98.5	2.89	15.51	.16	.11	81.33	
8	3.11	[b] 25.78	98.5	3.02	15.43	.16	.11	81.28	End of test. Flame went out

[a] Barometer 29.24 in. Hg. [b] Corrected to 30.0 in. Hg and 60° F.

In general, natural ventilation due to opening doors and leakage around the window casings will tend to keep the percentages of oxygen and carbon dioxide near that of normal air as well as to dissipate the carbon monoxide in proportion. The amount of natural ventilation will vary over a very wide range with different

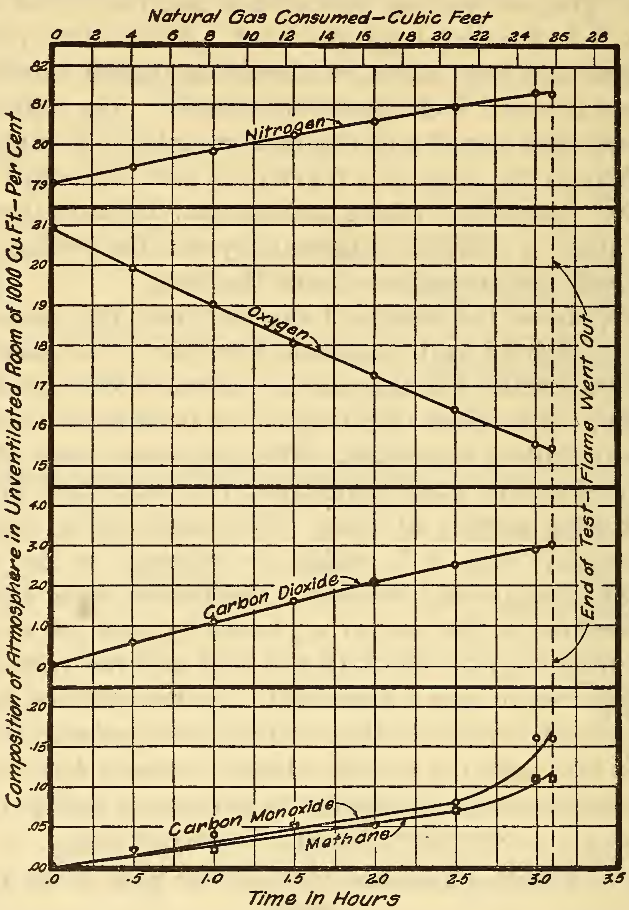

FIG. 3.—*Chart showing percentage composition in an unventilated room of 1000 ft.³ capacity as natural gas was burned in a top range burner at a rate of about 8 ft.³ per hour until the flame was smothered from deficiency of oxygen*

rooms and different seasons of the year, and it is therefore impossible to show accurate data as to what the values would be under practical conditions. On the other hand, the results of the test given in Table 4 show the maximum values to be expected from one burner where there is no natural ventilation and where the rate of consumption is about 8 ft.³ of natural gas per hour. If

the rate of consumption had been increased, or if more burners had been operated, the time that would have been required to cause the same smothering of the flame would have been proportionately decreased according to the rate of consumption.

It follows that if about 26 ft.^{3} of natural gas of the quality used in the tests of this report, under the conditions stated, are consumed in an unventilated room with a capacity of approximately 1000 ft.^{3} it will cause the flame to be extinguished from the diminution of oxygen. It is also evident that it is possible to have carbon monoxide present in an extremely dangerous quantity in poorly ventilated rooms where the yellow flame from natural-gas burners impinges against a utensil.

The fact that natural gas will not burn in an atmosphere where the oxygen content has been reduced to about 15.5 per cent explains why the flame from a burner is sometimes found extinguished when no one has caused it to be extinguished. This very seldom occurs except in winter months when proper ventilation is not observed. In the natural-gas regions deaths from smothering have occurred in extremely cold weather when people before retiring for the night have closed up the cracks around windows and doors so as to stop ventilation in order to retain the heat from a room heater and thereby have a warm room in which to sleep.

VII. CONCLUSIONS

Tests of the combustion products from burners using natural gas and burning in contact with utensils containing liquids at or below the boiling point of water show that carbon monoxide is liberated.

The quantities depend upon:

1. Distance of the utensil above the burner.
2. Height of blue inner cone of flame.
3. Type of burner.
4. Flame characteristic. (Ratio of volume of primary air injected into burner relative to volume of gas consumed.)
5. Rate of consumption of gas per hour.

It was observed that no carbon monoxide was found where the distance of the utensil from the burner was such that the blue inner cone of the flame did not touch the utensil.

For the same rate of consumption and same ratio of primary air to gas, one design of burner may permit the utensil to be placed as close as ¾ inch while another design may require a distance

of more than 1¼ inches in order that the amount of carbon monoxide be negligible.

For a given ratio of primary air to gas the highest percentages of carbon monoxide are produced when the utensil is placed so close to the burner as to cause a floating flame. When using the same burner with the utensil at a position that causes the flame to float, the carbon monoxide increases as the primary air rate is decreased. Therefore, a yellow flame will produce carbon monoxide at a rate greater than a blue flame.

Much of the carbon monoxide is surely produced by the smothering of the flame with the products of combustion which are hindered in their escape at the close positions of utensil from burner by the unavoidable baffling of the supply of secondary air. It is generally reported that carbon monoxide is produced by the chilling of the flame with a relatively cold surface.

Under the worst conditions found, the amount of carbon monoxide liberated per hour by the five gas burners tested was not enough to be dangerous to health unless one worked directly over the burner, or several burners were in use at the same time for several hours, or the room was unventilated.

Ventilation is essential where gas is consumed. A natural-gas flame will be smothered by the deficiency of oxygen when the oxygen content of the atmosphere has been diminished to about 15.5 per cent.

WASHINGTON, November 1, 1921.